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Historical trends in American coal production and a possible future outlook

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Abstract

The United States has a vast supply of coal, with almost 30% of world reserves (BP, 2008) and more than 1600 Gt (short) as remaining coal resources (Ruppert et al., 2002). The US is also the world's second largest coal producer after China and annually produces more than twice as much coal as India, the third largest producer (BP, 2008).

The reserves are concentrated in a few states, giving them a major influence on future production. Historically many states have also shown a dramatic reduction in recoverable coal volumes and this has been closely investigated. Current recoverable estimates may also be too high, especially if further restrictions are imposed. The average calorific value of US coals has decreased from 29.2 MJ/kg in 1950 to 23.6 MJ/kg in 2007 as U.S. production moved to subbituminous western coals (Annual Energy Review, 2007). This has also been examined in more detail.

This study also uses established analysis methods from oil and gas production forecasting, such as Hubbert linearization and logistic curves, to create some possible future outlooks for U.S. coal production. In one case, the production stabilizes at 1400 Mt annually and remains there until the end of the century, provided that Montana dramatically increases coal output. The second case, which ignores mining restrictions, forecasts a maximum production of 2500 Mt annually by the end of the century.

Key words:
USA; future coal production; peak coal; coal reserves; logistic model

1. Introduction

The American coal industry has a very long history going back to before the 19th century. In many ways, one can say that the industrial revolution of the United States was fuelled by coal (Figure 1). Anthracite from Pennsylvania quickly became popular as a household fuel in the growing cities when the more usual firewood was unable to meet demand. The rich Pennsylvanian coal fields were located close to big cities such as Philadelphia, while major railroads could easily deliver coal to the consumer. By the 1830s, hard coal production passed the Mt (short) mark (Milici, 1997), and continued to grow alongside the development of American industry and society.

Cities like Pittsburgh later became principal markets for bituminous coal, which was cheaper than anthracite, but generally contained less energy (gross calorific value ~30 MJ/kg compared to ~34 MJ/kg for anthracite) and more impurities, such as sulfur. Railway locomotives and stationary steam engines became major consumers in the wake of industrialization, subsequently coal output soared and before 1900 it doubled every ten years. By 1918, total production output passed the 600 Mt (short) mark (Milici, 1997). The Great Depression of the 1930s reduced output to 350 Mt (short) before it started to grow once more (Milici, 1997). By 1990, production broke the 1000 Mt (short) barrier and currently remains around that level (BP, 2008).

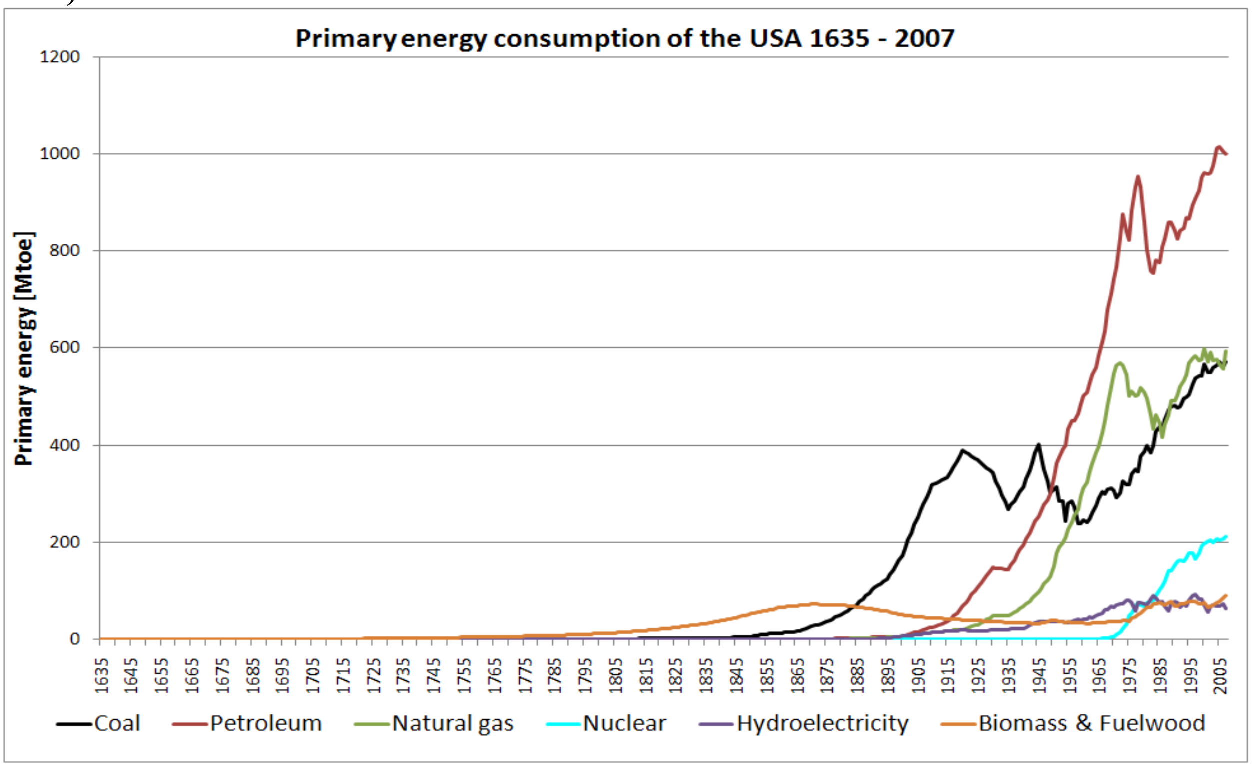

Figure 1: *Historical energy use of the United States from 1635 to 2000 in million tonnes of oil equivalents (Mtoe). Wood was replaced by coal in the end of the 19th century. Coal was the main energy source until petroleum and natural gas surpassed it in 1950 respectively 1958. Hydroelectricity has been stable at present output for many decades now, likely due to socioeconomic constraints and environmental restrictions preventing development of new rivers. Source: Annual Energy Review (2007)*

Pennsylvania and the rest of the Appalachian basin have produced coal since before 1800 and the region remains very productive. In many ways, the United States is a mature coal producer where the general geology is well-known and the most promising regions discovered and developed as well as the onset of long-term decline in key producers (Milici, 1996).

In 2006, around 50% of U.S. electricity was generated using coal (IEA, 2008). A large share of the steel industry was also coal dependent, either directly as coking coal or indirectly via coal-powered electric arc furnaces (Stubbles, 2000). The coal reserve is seemingly large and many believe that coal will be able to provide the United States with energy security and power future energy development. One example is how coal-to-liquids, based on American coal, has even been proposed as an idea to reduce dependence on imported oil and mitigate the effects of peak oil (Hirsch et al., 2005; Bunning and Obama, 2007) More discussion about coal-to-liquids, its feasibility and challenges can be found in Vallentin (2008).

2. Aim and methodology

The aim of this article is to provide an examination of the historical trends in American coal production and coal reserves. Coal is broadly divided into four ranks: anthracite, bituminous, subbituminous, and lignite (Carpenter, 1988; ASTM, 2005). There are many coal classification systems, but in this paper the energy content is seen as the most important factor. Anthracite and bituminous coal together form the high-energy hard coal class, while subbituminous coal and lignite has less energy content and may be called low-energy coals.

Coal is a finite natural resource and a model for extrapolation of production curves of finite resources was proposed by Hubbert (1956). His model assumes that production levels begin at zero, before the production has started, and ends at zero, when the resource has been exhausted. In between, the production curve passes through one of several maxima. The actual shape of the production curves may vary, but they are ultimately limited by the recoverable amounts of the finite resource. Hubbert (1956) proposed a bell-shaped curve for an idealized production behavior, representing various stages of maturity, without giving any exact mathematical description for it. Later, he used the simple logistic function (Hubbert, 1959) and developed his methodology even further (Hubbert, 1974).

Hubbert used a simple logistic curve because it had a theoretical basis, empirical agreement with a wide array of growth processes, as well as mathematical simplicity (Meng and Bentley, 2008). The theoretical foundation of logistic models stems from time series analysis, where a growth curve is limited by some saturation level (Mohamed and Bodger, 2005; Carrillo and González, 2002). The derivative of the logistic curve, often better known as the Hubbert curve, is frequently used in oil production forecasting. Its forecasting properties have been closely assessed by others (Laherrere, 2000; Brandt, 2007).

Analysis of the simple logistic function, its derivatives and related curves has been performed by Carlson (2007) and Brandt (2007). The disadvantage of the logistic curve is its symmetry, as empirical production data sometimes tend to be asymmetric in the post-peak region due to production enhancement techniques and potential reserve growth. For prediction of the peak year, both the simple logistic curve and the Hubbert curve are deemed equally well suited (Figure 2). Closer comparison of logistic curves, Hubbert curves, and Gaussian curves have shown no preference for either curve (Bartlett, 2000; Patzek, 2008). No forecast method is optimal and an array of various approaches should be used to establish a good picture.

We use the same basic approach as Hubbert (1959) to provide some possible future outlooks. What matters economically are produced volumes of coal, so discussion of future production is of greater importance than the state of future reserves. The single most important parameter in this approach is the assumption about the ultimate reserves, i.e. the maximum amount that can be produced under the production curve. In order to show alternative outcomes, different assumptions of the upper limit will be used. One case includes mining restrictions, as included in the reported recoverable volumes, and the other case use only the technical recoverability to estimate future coal production. Rules against mining activities in or near water streams or limitations for mountaintop mine waste dumping are examples of restrictions that can make portions of the technically recoverable coal unavailable for actual production, therefore affecting the upper limit in the model.

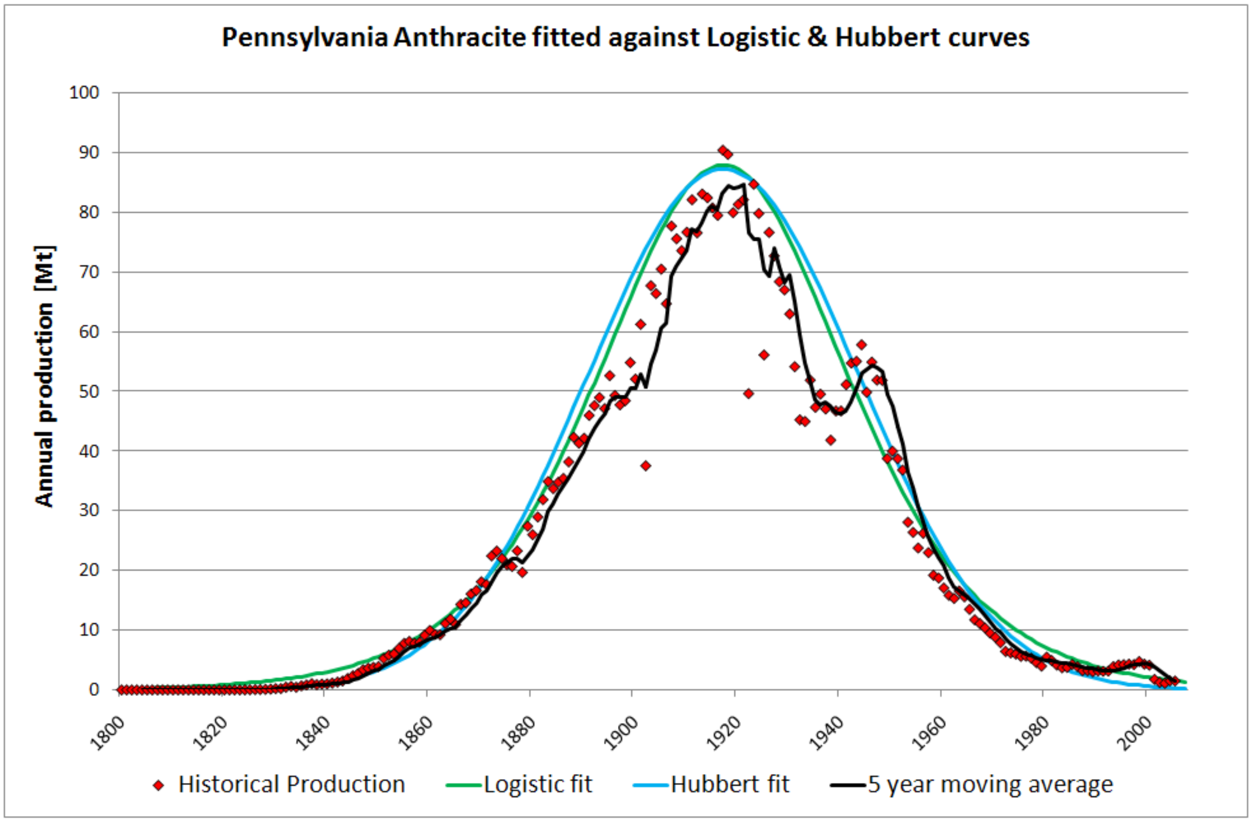

Figure 2*:* *Anthracite production of Pennsylvania fitted against both a logistic function and a Hubbert curve using the cumulative historical production and the proved reserve of 2006 as ultimately recoverable reserves. The logistic/Hubbert production behavior can be seen very clearly in this case and it is assumed that other states will follow a similar behavior in their coal production curves as they also are limited by some ultimately recoverable volumes. The differences between the logistic curve and the Hubbert curve are overall small. The small peak beginning in 1940s coincides with the Lend-Lease program for providing vast amounts of war material and goods to the Allies in Europe and later the war economy when the USA entered the Second World War. Consequently it is seen as a deviation from ideal behavior caused by politics. Data source: Milici (1997) and Quarterly Coal Report (1996-2007)*

In this paper, the sum of two logistic curves is used to fit historical data and forecast data for possible future production (Figure 3). This makes it easier to isolate historical production in the first curve, limited by the cumulative production, and keep the future production, limited by suitable estimates of future recoverable reserves, in the second logistic curve. The method does not include any other constraints than production availability and factors like CO_2 sequestration requirements or sulfur constraints will limit future production outlooks even more. The method used here can provide insight into the general long-term flow of finite energy resources, but perturbations caused by sudden and unforeseen near-term economic or political changes cannot be predicted. Therefore, long-term life-cycle projections should not be used as a substitute for meticulous economic studies to forecast perturbations in coal production over the next few years or decades (Milici and Campbell, 1997).

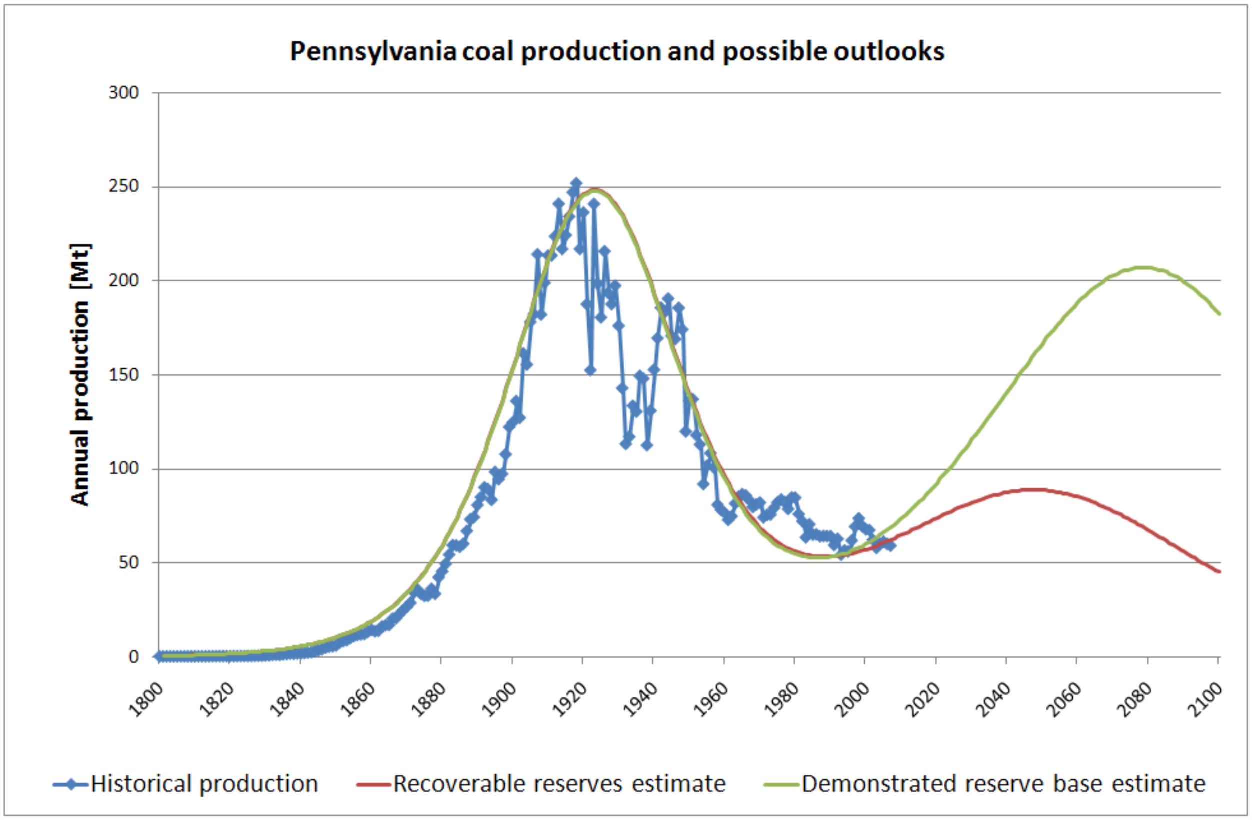

Figure 3: *Historical coal production of Pennsylvania and possible future production based on logistic curves in two cases. The recoverable reserves case uses cumulative production plus the reported recoverable reserves as an upper limit. The demonstrated reserve base (DRB) case uses the cumulative production plus the DRB, as defined by EIA (2006), as the upper limit. If the current reported reserves are valid, it should be possible for Pennsylvania to maintain production at current levels until 2080, whereas DRB allows increased production similar to the record levels of the 1910s. It should however be noted that the assumptions for the upper limits have significant impact on the outcome and choosing realistic and reasonable recoverable volumes is of great importance. Data source: Milici (1997) and Quarterly Coal Report (1996-2007)*

The logistic behavior can also be seen in many different countries that have passed their peak coal (Energywatch Group, 2007). As the best coal seams are depleted, mining became more expensive and complicated, thus reducing the attraction of coal as an energy source. Studies have already pointed out that the remaining coal reserves in the Appalachian basin are located in thinner, deeper coal beds than those currently being mined (Milici, 2000; USGS Northern and Central Appalachian Basin Coal Regions Assessment Team, 2001).

Depletion has proved to be an important factor in mining productivity and hence the entire economic competitiveness of coal production compared to other energy sources (Rodriguez and Arias, 2008). The relationship between the levels of reserves, depletion and extraction costs has been analyzed by others (Zimmerman, 1981; Harris, 1990; Epple and Londregan, 1993, Pickering, 2008). Several studies also state that depletion can make up for technological progress in the industry (Livernois, 1988; Rodriguez and Arias, 2008). The overall conclusion is that with increasing depletion of the best seams, mining costs increase and make coal less viable to consumers due to rising price. Environmental regulations and social acceptance are also factors influencing future production, but a comprehensive discussion of them are beyond the scope of this study.

2.1 Coal data gathering

The historical production data used here is primarily from the Coalprod database, compiled by the U.S. Geological Survey (Milici, 1997). It contains production data from 1800 to 1995, compiled from several state and federal sources such as U.S. Bureau of Mines Minerals Yearbooks (1933-1976) and U.S. Geological Survey Mineral Resources of the United States (1907 to 1926). See references in Milici (1997) for closer description of the data sources.

After that data from Energy Information Administration (EIA) publications, such as the Quarterly Coal Report (1996-2007) or the Annual Coal Report (2001-2007), have been used to create a production series from 1800-2007 for each state in the United States. Agreement with other sources for total US coal production, such as the BP Statistical Review of World Energy (2008), is good.

The reserve data has been taken from the mineral yearbooks of the U.S. Bureau of Mines together with various EIA publications and reports, such as Coal Industry Annual (1994-1999) and Annual Coal Report (2001-2006). For reserves of the entire United States, some values have been taken from sources such as World Power Conference (1924), World Energy Council (1934-2007), and the German Federal Institute for Geosciences and Natural Resources (BGR, 1980-2007). A historical reconstruction of the evolution of the recoverable reserves from 1924 to 2007 and from 1950 to present, even state-by-state, could be made.

2.2 Coal distribution in the US

United States coal reserves are located in three different areas (Figure 4). The Appalachian area is an important producer and production occurs in Pennsylvania, Eastern Kentucky, Maryland, Ohio, Alabama, Tennessee, Virginia, and West Virginia. The Appalachian area contains nearly all the U.S. anthracite and more than 40% of all estimated recoverable reserves of bituminous coal (EIA, 2007). The largest U.S. reserves of coking coal are located in central Pennsylvania and West Virginia.

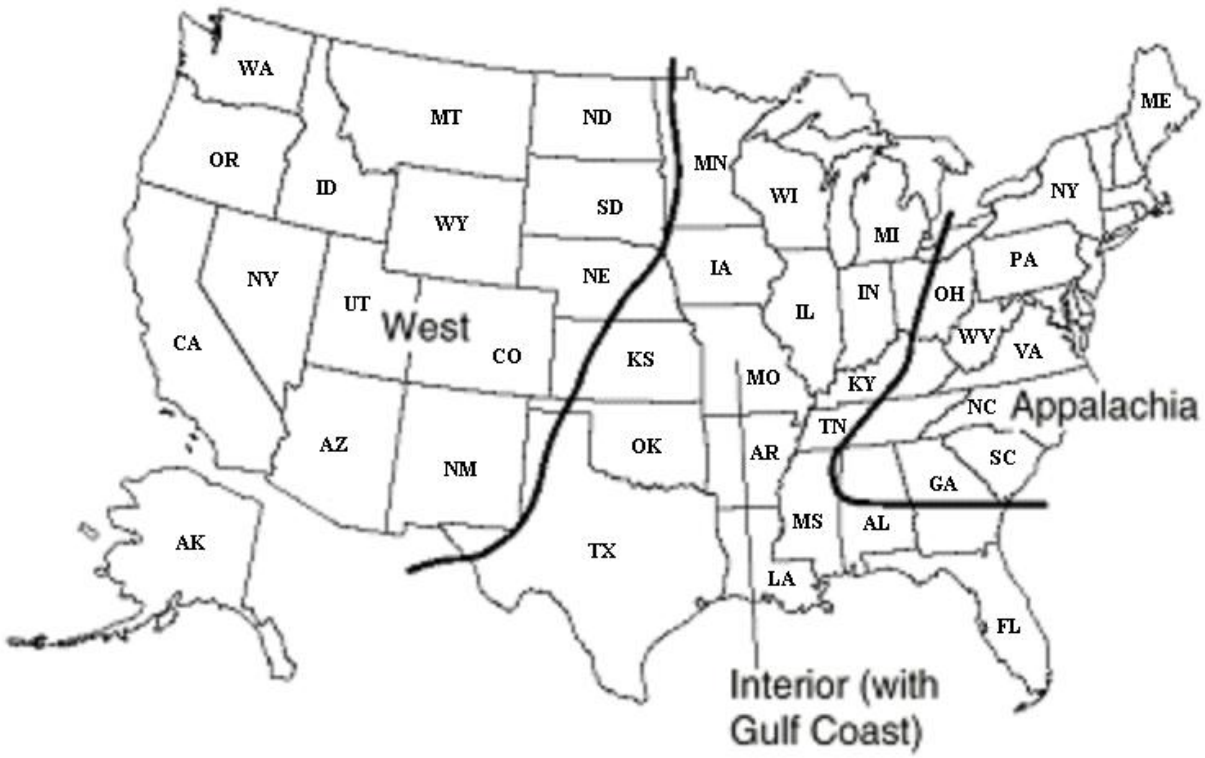

Figure 4: *Geographical display of the coal-producing areas of the USA used in this study. Actual coal production originates from coal beds not shown here. Adapted from Coal Reserves Database (1997)*

The interior area, consisting of Arkansas, Illinois, Indiana, Kansas, Western Kentucky, Louisiana, Mississippi, Missouri, Oklahoma and Texas, is the smallest producing area by volume (Annual Coal Report, 2007). Texas and the Gulf Coast Plain contain vast Cenozoic lignite formations (Ruppert et al., 2002). One major issue with Pennsylvanian coal from this area is its generally high sulfur content, more than 2.5% (EIA, 1989). A more comprehensive overview of the sulfur distribution within the Illinois basin, giving mean sulfur contents of 2.9-3.5% for important coal formations, can be found in Hatch and Affolter (2002). For Illinois, around 20 000 Mt coal, of a total recoverable reserve of 32 000 Mt, is located deep and with a sulfur content of over 2.5% (EIA, 1989). Because of the high sulfur content these coals are, at present, generally replaced by coal from other areas with less sulfur.

The Clean Air Act Amendments of 1990 (Environmental Protection Agency, 1990), restricting the use of high sulfur coals in power stations, had a significant impact on the demand for high-sulfur coals, mainly from the interior area, and resulted in an increased dependence on low sulfur western coals (O'Brien, 1997). Further environmental regulations, such as the Clean Air Mercury Rule (Environmental Protection Agency, 2005) were later proposed. The overturning of the Clean Air Interstate Rule and the Clean Air Mercury Rule by the United States Court of Appeals District of Colombia Circuit (2008a,b), makes the future even more uncertain. Obama's new administration signalized that new rules would be drafted to tighten the mercury emission control, instead of pursuing appeals of the Court's rulings (Cappiello, 2009).

The Powerplant and Industrial Fuel Use Act (1978) prohibited the use of natural gas in new power plants and encouraged the use of coal, nuclear and other alternative energy sources. The repeal of this act in 1987 set the stage for a massive increase in natural gas consumption, and gas became viewed as an economically efficient and environmentally friendly fuel compared to coal (EIA, 2005). This also influenced coal consumption patterns in the United States to a major extent.

The western area is by far the most productive (Annual Coal Report, 2007). Some bituminous coal is present, but most of the producing reserves are made up by subbituminous coal and lignite (USGS Central Region Energy Resources Team, 1999). The low-sulfur content of coal from this region has made them attractive as a replacement for high-sulfur coals (Tobin, 1984). Lower production costs have also been noted as an explanation for the rise of western coals (Ellerman et al., 2000).

3. Coal reserves and its evolution

The American coal classification system uses definitions that differ somewhat from other countries and organizations, such as the World Energy Council. A complete overview of the coal resource classification system used by the United States Geological Survey can be found in Wood et al. (1983). The *U.S.* Energy Information Administration (EIA) uses the definitions listed below for reserves (EIA, 2006). A full discussion of coal resources and reserve terminology as used by EIA, USGS, and U.S. Bureau of Mines can be found in EIA (1996). The "coal reserve" term used by EIA may better be described as "potential coal reserves", as they are generally not proved by detailed drilling (American Association of Petroleum Geologists, 2007).

Demonstrated reserve base (DRB) covers publicly available data on coal mapped to measured and indicated degrees of accuracy, and found at depths and in coal bed thickness considered technologically minable at the time of determinations. Mining losses, technical, and other restrictions are not considered. The DRB represents that portion of the identified coal resource, i.e. resources whose location, rank, quality, and quantity are known or estimated from specific geologic evidence as defined by Wood et al. (1983), from which reserves are calculated.

Estimated recoverable reserves cover the coal in the demonstrated reserve base considered recoverable after excluding coal estimated to be unavailable due to land use restrictions or coal currently economically unattractive for mining (and after applying assumed mining recovery rates). This category corresponds to *proved reserves* according to BP statistics or the proved recoverable reserves used by World Energy Council (2007). EIA creates this category by applying economic feasibility criteria factoring downward from the DRB. Closer discussions of

how availability of recoverable coal is estimated by the USGS can be found in Carter and Gardner (1989), Eggleston et al. (1990), or Luppens et al. (2006).

Reserves at active (producing) mines cover the amount of in situ coal that can be recovered by mining at presently active mines reporting to EIA. Non-commercial enterprises and inactive mines or formations are not included in this class.

Due to property rights, land use conflicts and similar limitations, only a certain percentage of the DRB is available for production. Currently the EIA estimates this percentage to be 50% (EIA, EIA, 2007), but in 1997, 54% of the total national DRB was deemed as recoverable (EIA, 1997). The percentage of the coal in the ground that has been considered as recoverable has changed dramatically over time and, generally, a downward trend can be seen (Table 1). For instance in North Dakota, enormous quantities of lignite were found and intensive surface mining started in the 1950s. The William J. Neil Electrical Generation plant near Velva began delivering electricity to the grid and, at that time, it was the largest coal-fired plant in the entire United States (North Dakota Blue Book, 1989). New plants were constructed and in the 1960s local government promoted massive development of the vast coal reserves. Local inhabitants soon stated that a "*one-time harvest*" of coal might make the land unsuitable for agriculture and substantial resistance against coal mining developed (North Dakota Blue Book, 1989).

Hence, the coal reserves of North Dakota were cut down from a recoverable reserve of over 270 000 Mt in the 1950s (assuming a recovery grade of 50%) to only 6239 Mt in 2006 corresponding to a DRB of 8178 Mt (U.S. Bureau of Mines, 1950; EIA, 2007). This reduction is truly spectacular. Many factors including reserve overestimations and new political regulations to changes in reserve classifications and better geological understanding of the regions played a role in this massive reduction. Production and the depletion-driven decline it eventually causes is also a plausible explanation for some states (Milici and Campbell, 1997). North Dakota is, however, far from alone in showing such a huge reduction of recoverable coal reserves.

In 1924, coal reserves of the US were estimated to be 3,838,657 Mt based on a *minimum thickness of seams, workable to a depth of 4000 feet from the surface, as 1 foot and between depths of 4000 to 6000 feet as 2 feet with 6000 feet regarded as the limit to workable depth* (World Power Conference, 1924). In 1936, the same source states a recoverable reserve of 2,889,027 Mt (World Energy Council, 1936). In comparison, the recoverable reserve in 2006 is only 6 % of what it was in 1924.

Whether this depends on past overestimation of the recoverable reserves, change of classification systems over the decades, or other factors is hard to tell. The important conclusion is that the recoverable reserves have decreased substantially over time and the exact cause of this is probably a multitude of factors (Figure 5). Political and environmental factors probably played an important role, but a comprehensive discussion of the causes behind the reductions is beyond this study.

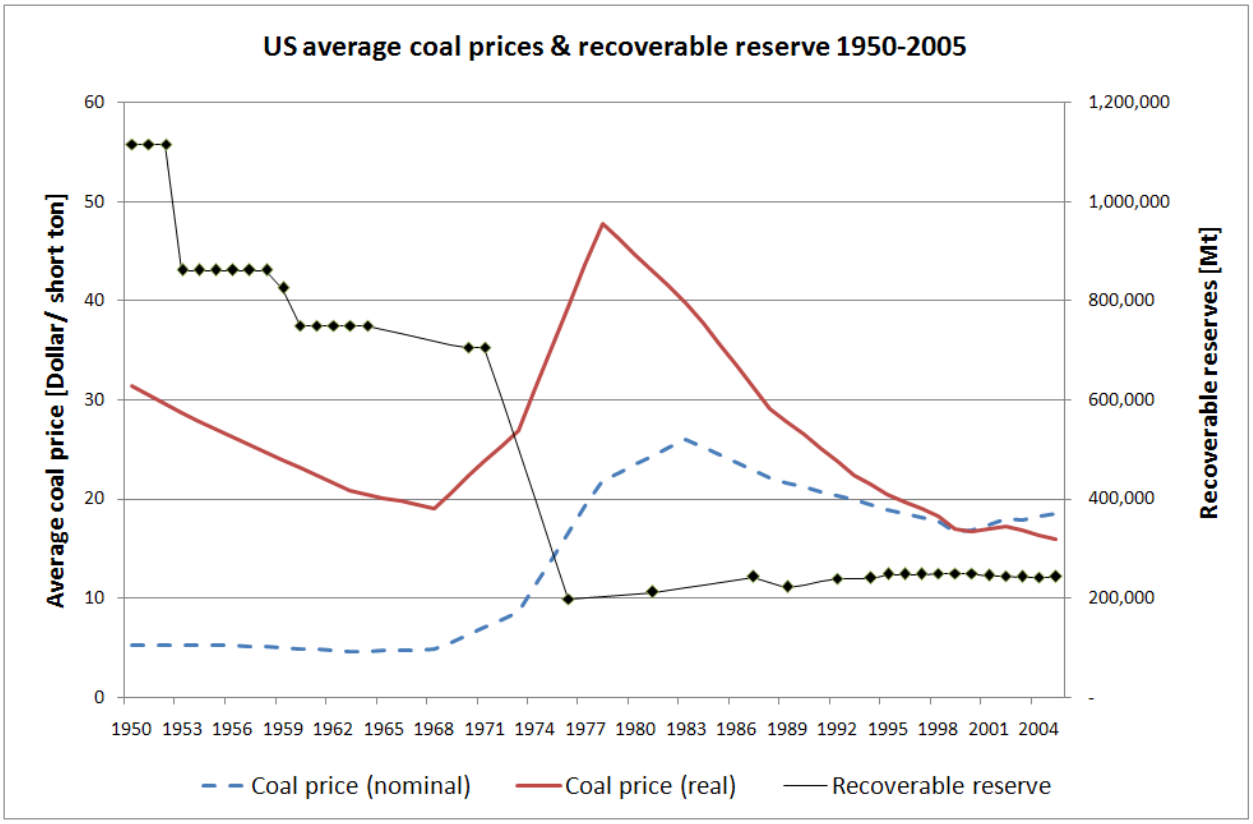

Figure 5: *Average U.S. coal prices and recoverable reserves. The nominal price is given in dollars of the day, while the real price is given in inflation adjusted 2000-dollars per short ton. A significant reduction in the recoverable reserves occurred in the 1970, despite concurrent major increases in coal price. Since the 1980s the recoverable reserve seems to be more or less constant. Reserve estimates for a given year is shown by a black diamond, while the black line shows the interpolation for years without reserve data. Source: Coal Industry Annual (1994-1999), Annual Coal Report (2001-2006), EIA (1989), World Energy Council (1976-2007) and U.S Bureau of Mines Minerals Yearbook (1933-1976)*

National Petroleum Council (2007) claims that the foundation (Averitt, 1975; USGS 1976) for assessment of American coal supply is also old and was systemized in 1974 by the U.S. Bureau of Mines, implying that a more modern assessment is needed to create a reliable estimate of the future coal supply. In retrospect, USGS primarily focused on resources, while U.S. Bureau of Mines focused on reserve estimates. The U.S. National Academies (2007) declared that current U.S. reserve estimates may be overstated and recommends that USGS undertake a new assessment of domestic coal reserves and resources. The latest results and updates of coal resources by the U.S. Geological Survey can be read in more detail in Ruppert et al. (2002). In recent years, USGS has also performed a number of coal availability studies, such as Luppens et al. (2008) and USGS Northern and Central Appalachian Basin Coal Regions Assessment Team (2001).

Table 1: *Estimated recoverable reserves state by state for the United States in Mt. Many states show large downward revisions since 1950, most notably North Dakota and Colorado. The reserves for Kentucky include both eastern and western parts. Pennsylvania includes all coal reserves, i.e. both anthracite and bituminous coal. Sources: U.S Bureau of Mines Minerals Yearbook (1950-1970), EIA (1989), Coal Industry Annual (1996), Annual Coal Report (2006)*

State	Recoverable reserves 1950	Recoverable reserves 1960	Recoverable reserves 1970	Estimated recoverable reserves 1987	Estimated recoverable reserves 1995	Estimated recoverable reserves 2006
Alabama	**29,086**	**5,764**	**6,096**	**2,825**	**2,738**	**2,510**
Alaska	**NA**	**42,924**	**59,005**	**2,457**	**2,421**	**2,569**
Arkansas	**697**	**1,100**	**1,097**	**170**	**207**	**207**
Colorado	**143,532**	**36,638**	**36,596**	**9,517**	**9,159**	**8,824**
Georgia	**412**	**34**	**8**	**NA**	**2**	**2**
Illinois	**75,133**	**59,139**	**63,191**	**32,105**	**30,816**	**34,453**
Indiana	**21,356**	**15,867**	**15,723**	**4,610**	**3,927**	**3,653**
Iowa	**12,916**	**12,903**	**2,955**	**1,132**	**1,022**	**1,022**
Kansas	**7,962**	**9,411**	**8,971**	**606**	**620**	**617**
Kentucky	**54,169**	**30,402**	**29,633**	**14,356**	**14,749**	**13,413**
Maryland	**3,412**	**539**	**533**	**435**	**374**	**323**
Michigan	**99**	**93**	**93**	**NA**	**54**	**54**
Missouri	**35,764**	**30,294**	**10,587**	**3,527**	**3,494**	**3,489**
Montana	**100,330**	**100,564**	**100,560**	**64,935**	**68,391**	**67,949**
New Mexico	**36,045**	**30,602**	**27,877**	**2,836**	**7,452**	**6,319**
North Carolina	**49**	**50**	**50**	**NA**	**5**	**5**
North Dakota	**272,092**	**159,082**	**159,053**	**6,780**	**6,553**	**6,239**
Ohio	**46,749**	**19,143**	**18,858**	**9,629**	**10,630**	**10,402**
Oklahoma	**24,790**	**1,504**	**1,492**	**830**	**740**	**724**
Oregon	**NA**	**88**	**19**	**NA**	**8**	**8**
Pennsylvania	**33,217**	**32,151**	**31,512**	**11,167**	**11,358**	**10,602**
South Dakota	**280**	**921**	**922**	**251**	**251**	**251**
Tennessee	**11,346**	**862**	**1,187**	**475**	**445**	**414**
Texas	**14,004**	**6,749**	**4,950**	**9,991**	**9,124**	**8,609**
Utah	**42,158**	**11,993**	**14,616**	**3,146**	**2,722**	**2,449**
Virginia	**9,295**	**4,848**	**4,458**	**1,459**	**1,236**	**712**
Washington	**28,845**	**28,759**	**2,804**	**734**	**661**	**618**
West Virginia	**50,193**	**47,128**	**45,882**	**19,156**	**17,825**	**16,161**
Wyoming	**54,806**	**57,493**	**54,742**	**39,306**	**41,189**	**36,418**
Other states	**7,417**	**2,091**	**2,141**	**533**	**315**	**283**
U.S.A. Total	***1,116,153***	***749,137***	***705,610***	***242,966***	***248,488***	***239,297***

To conclude, one can see that the recoverable reserves have been constantly reduced over the decades, despite new technologies and periods of increased coal prices. In agreement with the findings of Livernois (1988) and Rodriguez and Arias (2008), one can thereby state that depletion has offset much of the gains that technological progress has produced. The reason for this is simple. The coal seams get more and more complicated and labor-intensive to mine due to depletion, resulting in higher production costs while new technologies and mining methods reduce the mining costs to some extent.

Land-use regulations, various laws, such as federal laws that prevent mining near homes, public buildings or federally funded highways (Eggleston et al. 1990), and environmental conventions are also likely to have played a role in the disappearance of the vast recoverable reserves over time. Mining subsidence damage is a main factor for coal mining restrictions beneath existing buildings (Guo et al., 2007). With an increased number of houses, roads, and other buildings, it is reasonable to assume that this has prevented coal mining in some areas. Smog and particle emissions are another problem that has led to restrictions affecting coal. A strong connection between air quality regulations and demand for low-sulfur coal has been observed by others (Tobin, 1984; O'Brien, 1997). However, it is beyond the scope of this study to investigate mining subsidence, ecological impacts, and social acceptance in any detail.

The impact on water and effects on vegetation is another important topic, especially in those places where agriculture and coal mining clash. These problems include acid mine drainage, acid rain, Hg and other pollutants. Similar issues have been carefully discussed by others (Larsen and Mann, 2005; Blodau, 2006). The impact of coal mining, primarily surface mines, on animals, local wildlife and vegetation has been investigated by various studies (Knotts and Samuel, 1981; Lewin and Smoliński, 2006, León et al., 2007). Consequently, increased care for protection of wildlife and biological diversity has probably decreased the areas available for coal mining and, thereby, also the recoverable reserves.

Better geological understanding is also a reasonable explanation for the massive reductions of the recoverable reserves. Incomplete data, geological variations, and generalizations of mining methods have been proposed as factors for discrepancies in the U.S. coal assessments (van Rensburg, 1982). The resource assessments are of course important, but when it comes to reserve estimations both economical and regulatory considerations must also be included. The amount that actually can be recovered is far less than all the coal that is geologically available and this distinction should always be noted.

In reviewing the historical evolution of coal reserves, one can state that the trend here does not point towards any major increases in available recoverable reserves; rather the opposite is true due to restrictions and increased focus on environmental impacts from coal extraction. Although technological advances and changes in economic conditions have influenced coal reserves, utilization is, and will continue to be, the largest factor in coal depletion. The development of new even stricter regulations and environmental laws is also a reasonable assumption and this will further limit the amount of recoverable coal. A major relaxation of mining restrictions or regulations is not considered, as it would be out of line with the historical trends. Thus, the current coal reserves can be viewed as a reasonable proxy for remaining recoverable coal volumes in the future. This also implies that the present recoverable reserves are a useful, and maybe even optimistic, upper limit for models of future production.

4. Coal production

The Appalachian area is historically the most important producer in the United States. The cumulative production of the Appalachian region accounts for more than 63% of the U.S. total, with the other regions slightly below 20% (Milici, 1997). Production from the western area, i.e. the state of Wyoming and the Powder River Basin, is currently growing very rapidly and accounts for around 40 % of total U.S. coal production (Annual Coal Report, 2007). The clean coal from Powder River Basin is mixed with high-sulfur coals to meet air quality regulations.

US coal production has been dominated by a few productive states. The most important states are Pennsylvania, Kentucky (eastern), West Virginia, Illinois, West Kentucky, Texas and Wyoming, since these states are the only ones that have ever produced more than 50 Mt of coal annually (Milici, 1997). Together these seven states account for over 75% of the cumulative coal production of the United States, with Pennsylvania as the most important contributor with nearly 25% (Figure 6). By the beginning of the 1820s, Pennsylvania produced over 75% of the total U.S. coal output (Milici, 1997). Today its share is only around 6%.

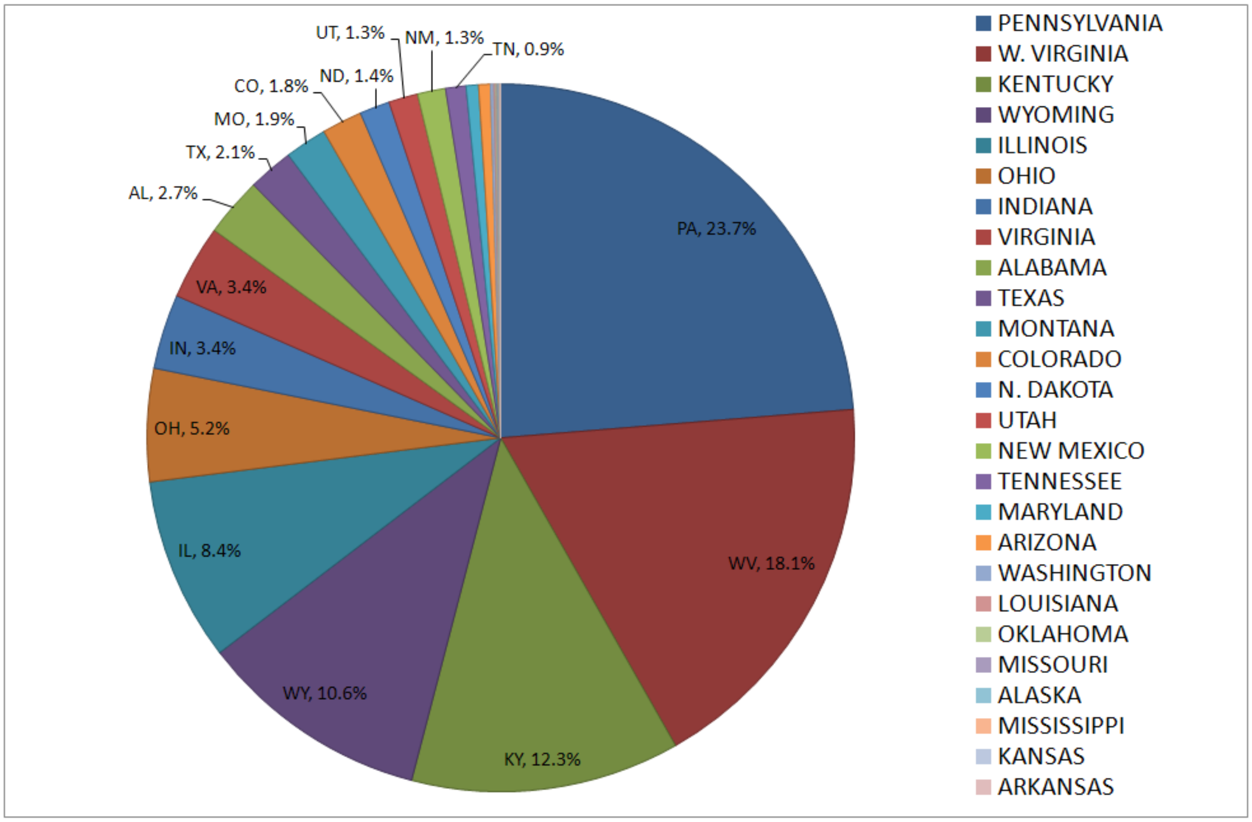

Figure 6: *Share per state of the total cumulative production of the United States in descending order starting from Pennsylvania. The three states Pennsylvania, West Virginia, and Kentucky from the Appalachian area accounts for over 50% of the total cumulative coal production. Wyoming, with it's over 10% share, accounted for 40% of the current U.S. coal output by volume in 2007.*

4.1 Appalachian area

In the Appalachian area, many of the states show typical post peak production behavior. Pennsylvania, Virginia, and East Kentucky coal production is in decline; West Virginia is not. Most other states have a low production level and low recoverable reserves. To conclude, this basin is a mature region and shows behavior typical for mature oil and gas producing regions.

The Appalachian area has been able to maintain more or less stable production since the beginning of the 20th century (Figure 7). Increasing production costs due to depletion and difficulties in keeping up with demand have been characteristics for this basin in recent years (Milici, 2000). The highest quality and thickest coals have already been found and exploited, leaving those seams that are of lower in quality, thinner, and more difficult to mine. The ultimate decline for this area is may be in the near future, indicated by depletion of the major producing beds (Milici and Campbell, 1997; Milici, 2000), perhaps as soon as a few years to a decade depending on the economic conditions.

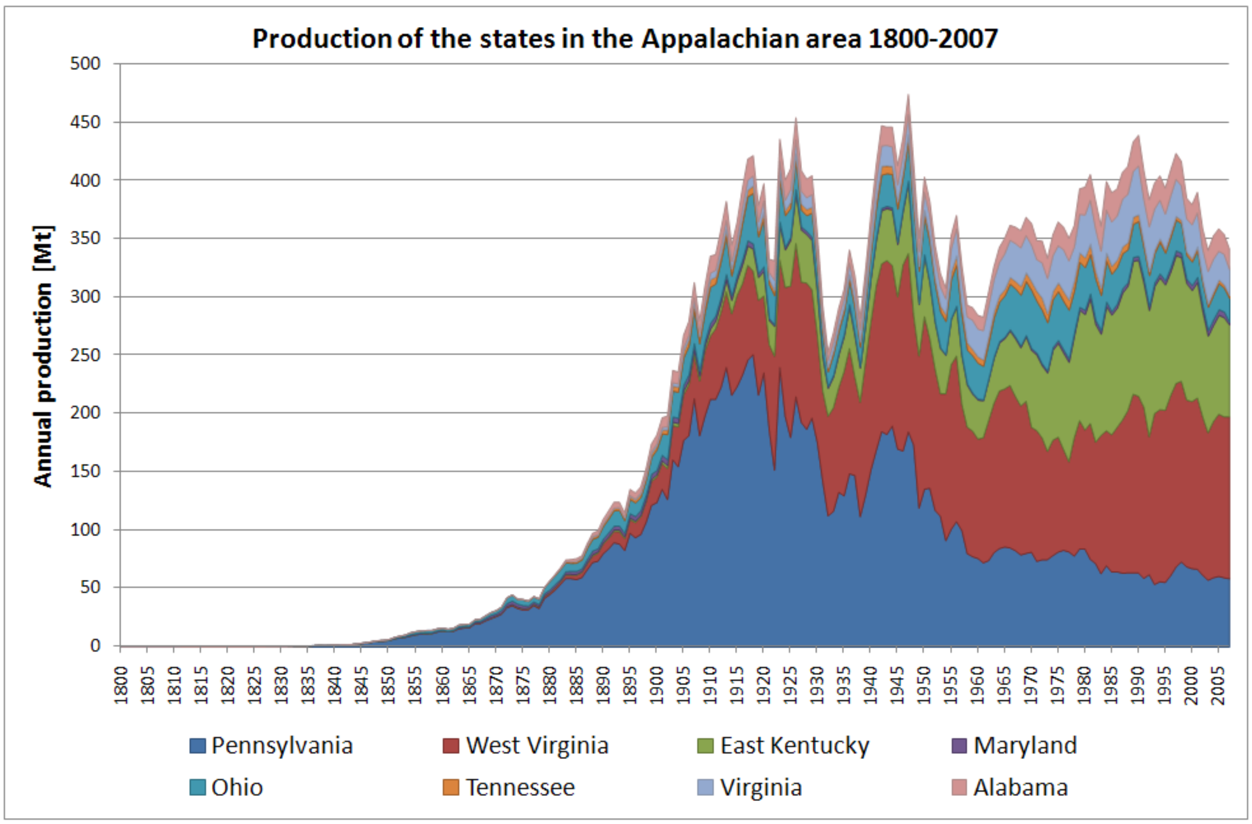

Figure 7: *Share per state of the total cumulative production of the United States in descending order starting from Pennsylvania. The three states Pennsylvania, West Virginia, and Kentucky from the Appalachian area accounts for over 50% of the total cumulative coal production. Wyoming, with it's over 10% share, accounted for 40% of the current U.S. coal output by volume in 2007.*

Another way of displaying the production behavior of the Appalachian area is to use a technique called Hubbert linearization. This method is based on rewriting the Hubbert equation and obtaining a linear relationship, which more easily can be extrapolated to estimate ultimate

reserves (Brandt, 2007). It should be specifically noted that this method places cumulative production on the x-axis, not year. The displayed years are only shown to retain a connection to the actual time scale and show when in time particular trends emerged.

One can find two different trends in the Appalachian coal production (Figure 8). The first trend, coinciding with the rapid expansion of production, started in the 1830s and was steady until early 1950s when the second trend emerged. The second trend can be seen as a prolonging of the plateau phase where new mining methods, such as the controversial mountain top removal mining, have been used to allow production from remaining unexploited seams. This change in trends coincides with the reductions of recoverable reserves discussed earlier in this study.

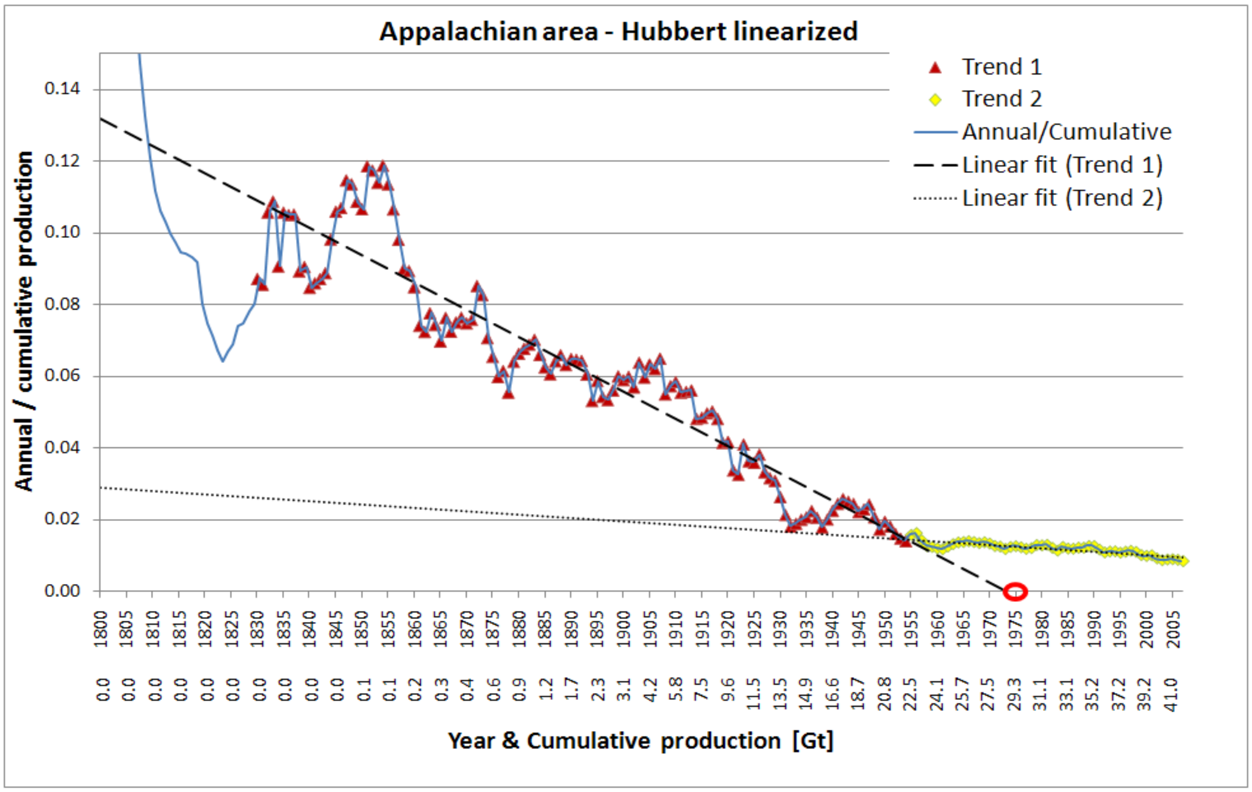

Figure 7: *Hubbert-linearized plot of the coal production from the Appalachian basin. Two different production trends can be seen. The first one started in 1830 and continued until 1950s, pointing towards an ultimate recoverable reserve of 30 Gt. The other trend started in mid 1950s and is a much flatter trend, pointing towards very high cumulative production. However, it should be noted that extrapolation of a very flat trend seldom leads to reliable results as a small difference in gradient can give enormous differences in ultimate reserves.*

4.2 Interior area

The interior area displays a similar behavior with a small number of dominating states (Figure 9). The most important one is Illinois, which has both vast reserves and significant levels of historic production. Several of the states in this region contain mostly lignite, such as Texas, Louisiana, and Mississippi. Today the entire region seems to be in decline or at low levels of production.

The high sulfur content, with mean values of 2.9-3.5% for important Illinois Basin coal beds (Hatch and Affolter, 2002), makes them presently unattractive. Installation of SO_2-controls by utilities would allow these coals to be easier used. The future fate of coal production in this area is closely connected to the development of regulations or technologies for clean usage of the high-sulfur coals. Gulf Coast lignites do not have as high sulfur content as Illinois Basin coals, and may be seen as an exception in the interior area.

As in the case with the Appalachian Basin, two different trends can be seen for the interior region in a Hubbert linearized plot (Figure 10). The first pioneering era of coal production and its trend came to an end in the 1940s and was replaced by a much flatter trend that has remained steady since 1940s.

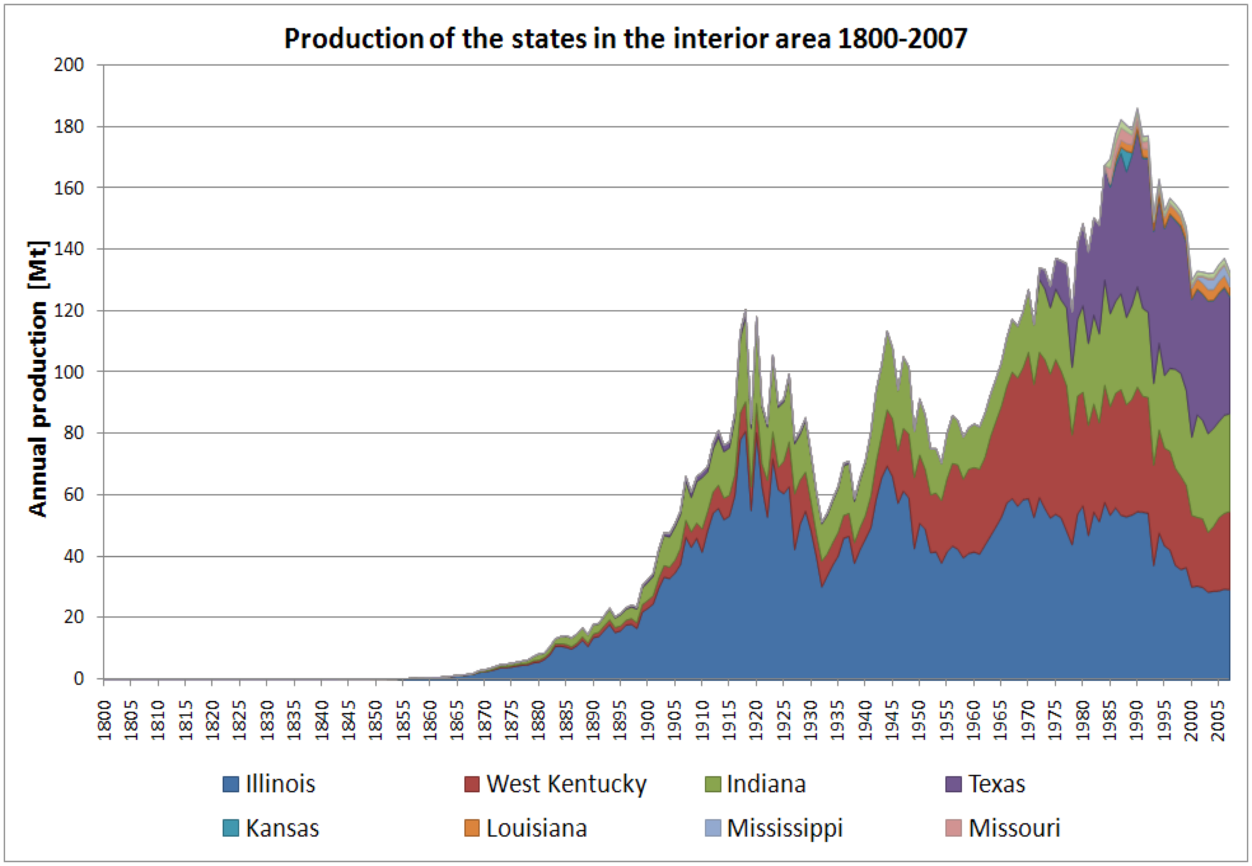

Figure 8: *Coal production of the interior area. The area has been historically dominated by Illinois, but after 1990 when the Clean Air Act was introduced the demand for its high-sulfur coal decreased and so did its production (Tobin, 1984). Western Kentucky, Indiana, and Texas are other major producers in this area, but since 1990, the output of most states has declined.*

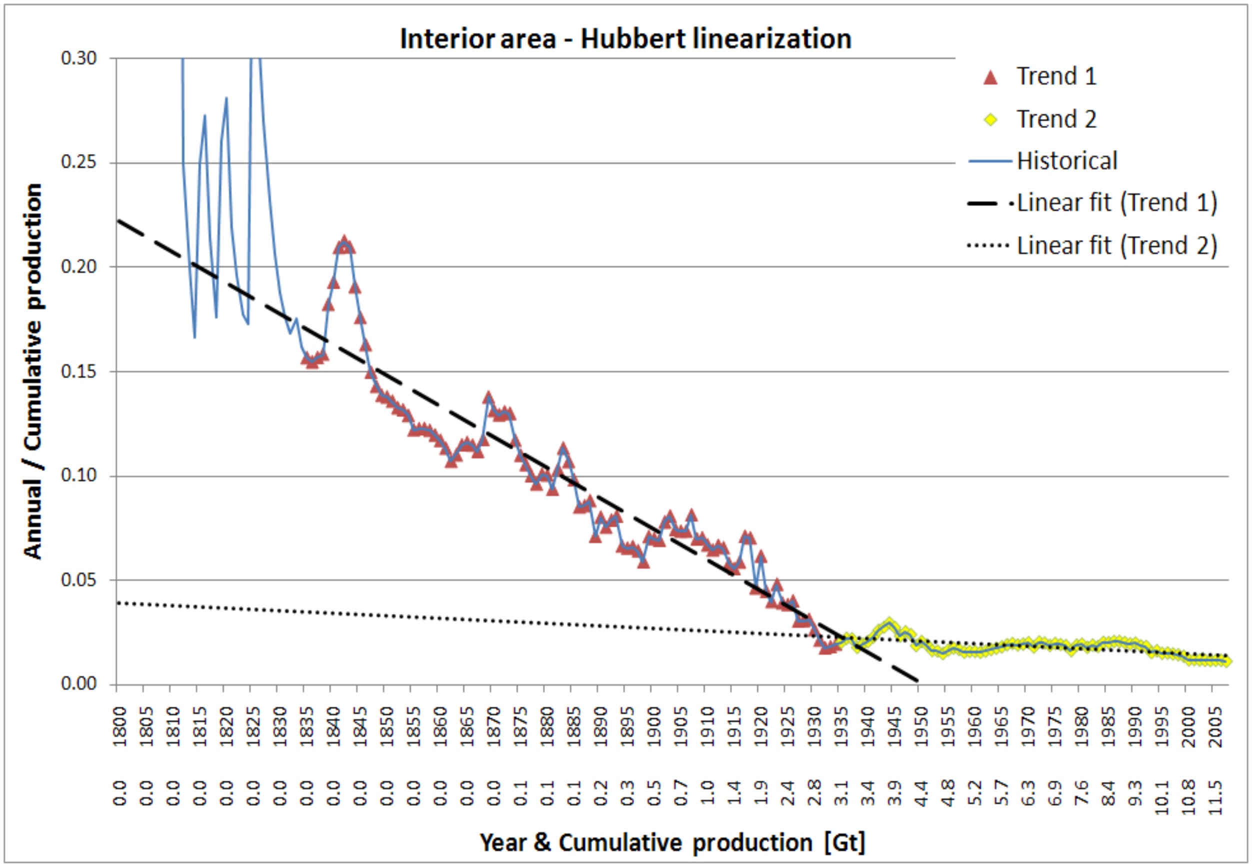

Figure 9: *Coal production from the interior area in a Hubbert linearized plot. Also here one can spot two different production trends with a change around the 1940s. Again, a very flat trend has been recently assumed and hence makes it hard to forecast the ultimate production from this region.*

4.3 Western area

The last major coal producing area in the United States is the western area (Figures 11 and 12). This area contains more than 500 Gt of subbituminous coal resources in the Powder River Basin (USGS Central Region Energy Resources Team, 1999). The low sulfur content of the western coals has made them attractive as a replacement for, or for mixing with high-sulfur coals of the interior area to meet air quality regulations.

The Powder River basin (Montana and Wyoming), has the largest proportion of the recoverable reserves (Annual Coal Report, 2007). Montana has the largest coal reserves in the United States, however, Wyoming is the dominant producer, accounting for over 70% of total coal production for the area in 2007 (Annual Coal Report, 2007). Significant difference in severance tax between Wyoming and Montana is a reason for the differences in production volumes and development (Hertzler, 1994). All other states have relatively small production volumes, typically well below 40 Mt annually. The western area is by no means as mature as the other two coal areas. The industry is still young here and much of the production comes from enormous surface mines, most notably in the Powder River Basin.

CO_2-emission regulations are a probable future event. This will likely be a dominating factor for future coal price in all areas and decrease coals' economical feasibility compared to

alternative energy sources. Such events should be seen as additional constraints for future production, compared to the idealized curves used for forecasting in this paper. CO_2 regulation and similar factors require careful economical analysis (Milici and Campbell, 1997), and should be performed as a complement to the long-term outlooks done in this study.

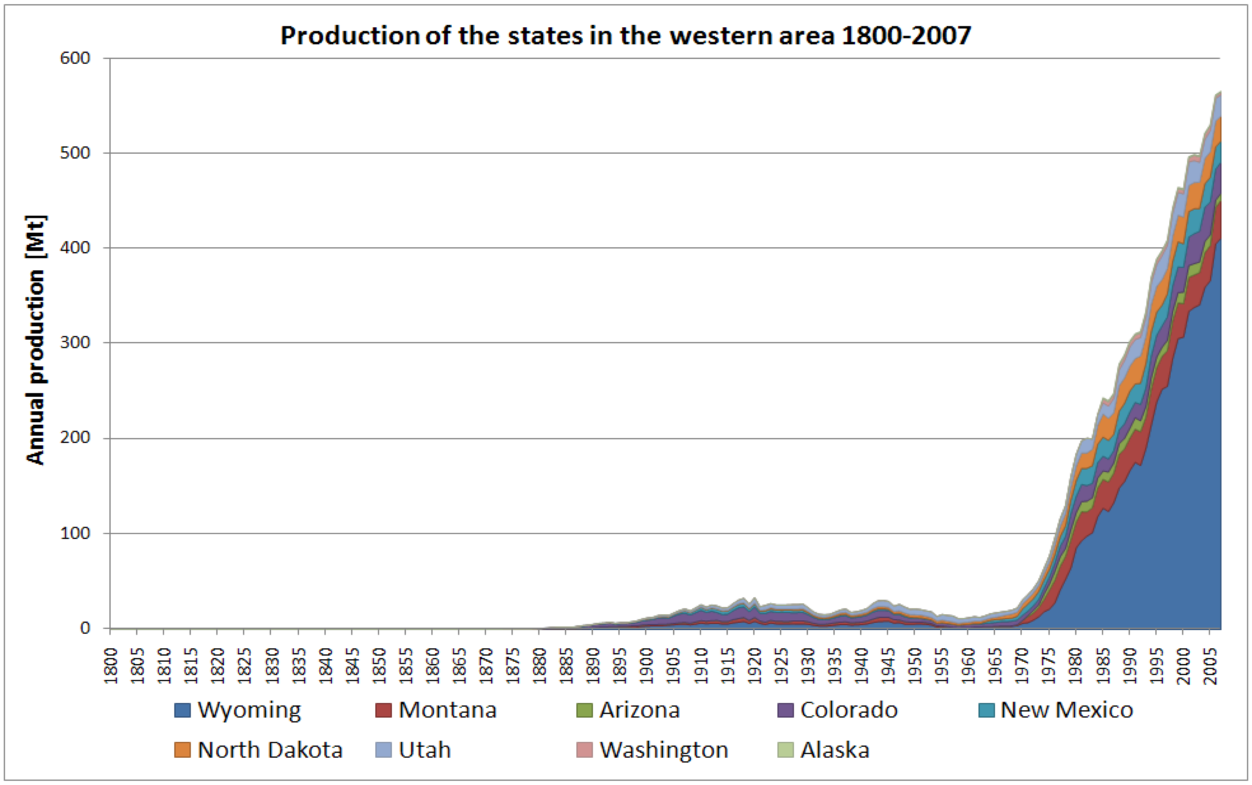

Figure 10: *Coal production of the western area. Virtually no coal was mined in the western region until the beginning of the 20th century, likely due to low energy content and remoteness from markets. It was not until the 1970s that coal production started to increase dramatically, driven by lower production costs (Ellerman et al., 2000) and by the Clean Air Act of 1970 and its amendments in 1977, which promoted low-sulfur coals (Tobin, 1984; Hertzler, 1994; Milici, 2000). Wyoming is totally dominating this area and is the only state that has significantly increased its production. All the other states have remained at low production levels less than 40 Mt annually, despite vast reserve numbers in some cases.*

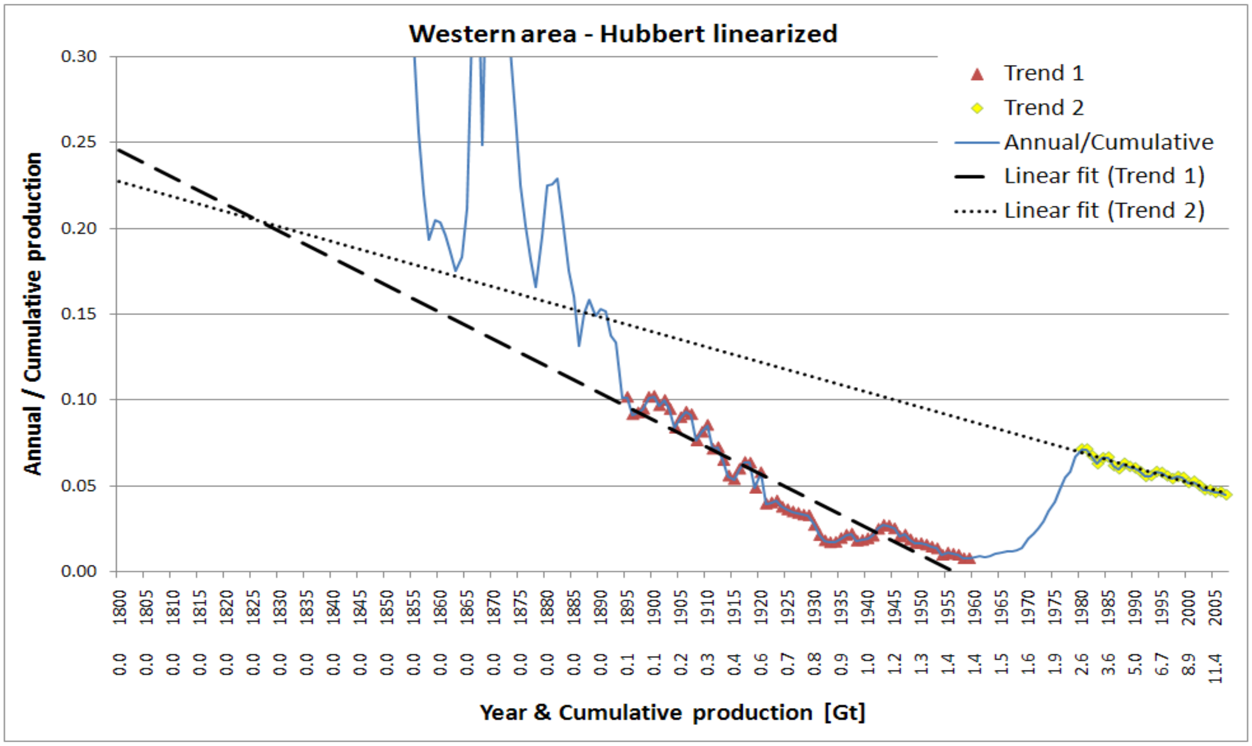

Figure 11: *Production of the western area in a Hubbert linearized plot. Two different trends can be seen but it is different from the observed trends in the Appalachian and interior areas. Two relatively steep trends appear and the last one, starting in 1980, is strongly driven by Wyoming.*

5. Calorific value decline

Another sign of increased depletion of U.S. coal can be seen in the declining energy content of extracted coal. As the best coals with high energy content are extracted, then new coal with relatively lower content must be produced to satisfy demand. This trend, and the decreased net energy production it brings, has been noted in several studies (Cleveland et al., 1984; Cleveland, 2005).

A part of this calorific value decline can be explained by the increased production of subbituminous coal starting in 1970s, but others have noticed that even within all coal ranks the calorific value is decreasing (Energy Watch Group, 2007). This trend has been noted since the 1950s and it is therefore likely that both depletion, most notably in the Appalachian area, and increased dependence on subbituminous coal will continue to affect the average energy content of produced coal. The possible production increases of high energy coals from the interior area are not likely to significantly offset the overall production decrease due to depletion of high energy coals in other areas by 2030. All this serves as a justification for an extrapolation of the trend into the future to form an estimate of the average energy content of U.S. coals (Figure 13).

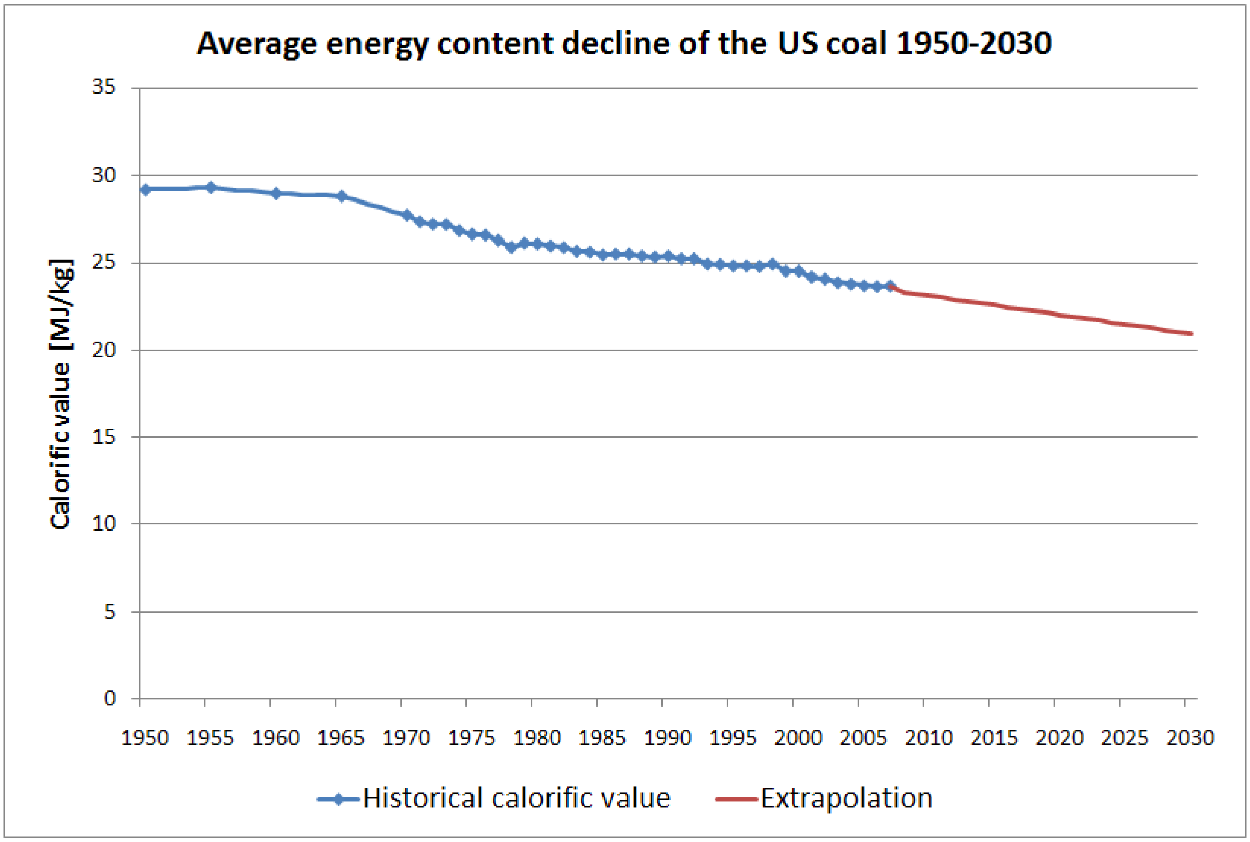

Figure 12: *Declining calorific value of the U.S. coal delivered to power plants and combined heat and power plants according to EIA. From 1950 to 2007, the average energy content has dropped significantly. The explanation for this is the decreased production of bituminous coal and the increased volumes of low-energy coal into the U.S. coal production, along with the depletion of the easy accessible, high calorific value coal, and imposed restrictions of various kinds. This trend is assumed to continue in the future and by 2030 the average energy content would be slightly above 20 MJ/kg. Data source: Annual Energy Review (2007)*

The extrapolated data set gives a future average energy content of US coal of 20.89 MJ/kg by 2030. The International Energy Outlook (2007) claims that the total energy produced from American coal 2030 will be 35.8 EJ, using the extrapolated calorific value yields a resulting production volume of 1712 Mt. This is a significant increase from the production volume of 1039 Mt in 2007 (BP, 2008). Our analyses suggests that it will not be likely that such an increase can occur because of the huge number of new mines, miners, equipment, and permits needed to achieve such an increase. It is questionable if the required increase is even possible given falling production trends in many U.S. regions. The lack of suitable new coalfields and the potential problems with political acceptance, land-use conflicts, and legislation also argue against increased production.

It is important to look at U.S. coal production by energy content to develop a better understanding of all possible future outcomes. The lignite-producing states include Louisiana, Mississippi, Texas, and North Dakota. Subbituminous coal production occurs in Alaska, Montana, Washington, and Wyoming, all of them located in the western area. All other states are assumed to produce anthracite and/or bituminous coal. A more comprehensive and detailed

division of the coal rank in each area can be done, but for simplicity only the coal rank that is chiefly produced for each state will determine the entire states' coal output.

For the purpose of our model, lignite was converted to energy units by using the conversion factor of 0.39 metric tons per ton of oil equivalent (toe), based on the average energy content of American lignite (National Mining Association, 2008). Subbituminous coal was converted using a factor of 0.49 ton/toe and anthracite/bituminous coal 0.67 ton/toe (National Mining Association, 2008). More detailed mappings of typical calorific values in individual coal beds can be found in Bragg et al. (1998) or USGS Northern and Central Appalachian Basin Coal Regions Assessment Team (2001).

United States production of coal, in terms of energy, has been in a plateau phase since 1998. The plateau has been within the 4 % fluctuation band that Hirsch (2008) defined as the limits for the plateau phase (Figure 14). Despite increased energy prices and demand for more energy, this plateau phase has lasted for ten years.

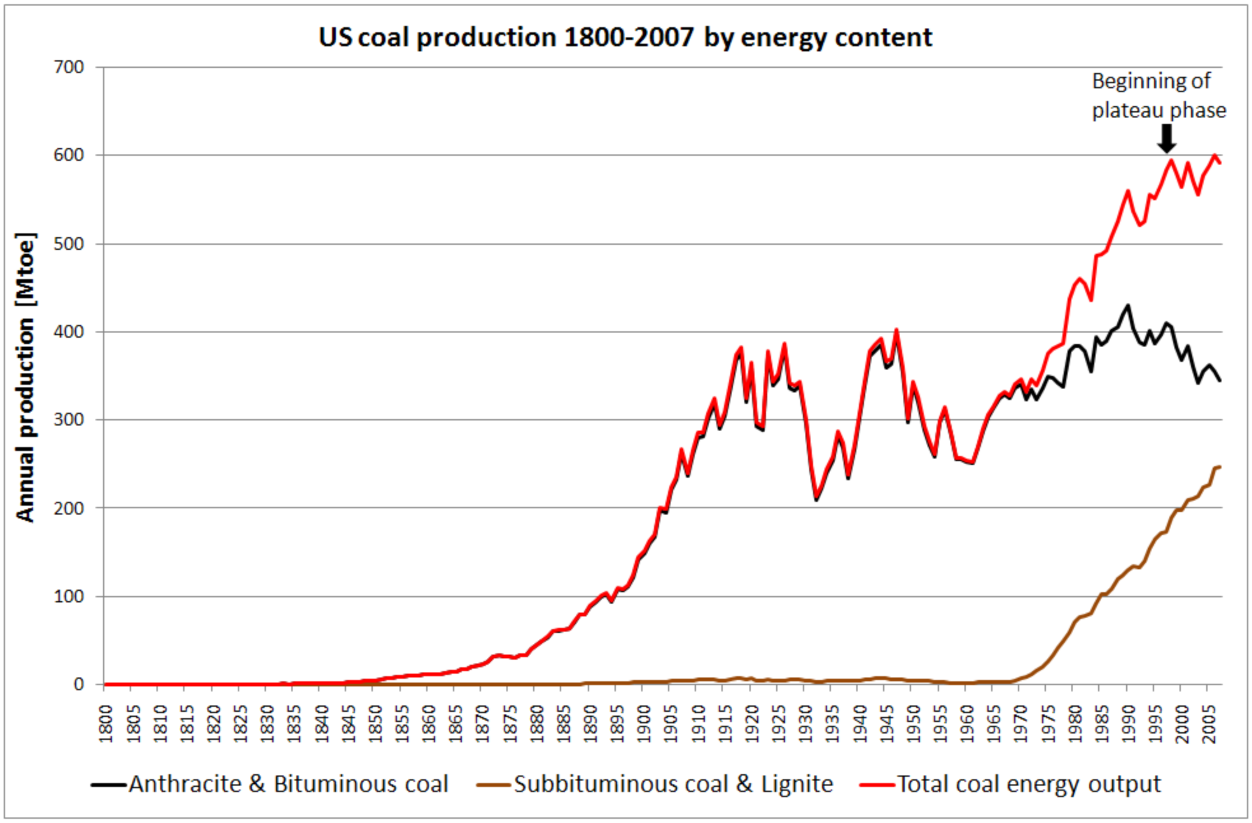

Figure 13: *The U.S. coal production from 1800 to 2007 by energy content. Anthracite and bituminous coal are regarded as high-energy coal, while subbituminous coal and lignite are regarded as low-energy coal because of the differences in calorific value. The energy output from high-energy coal peaked in 1990 and has been in decline since then. The energy output of low-energy coal has increased rapidly since the 1970s. The total energy output has been flat since 1990, despite increased production volumes.*

A major factor behind the decrease in production of high-energy coal is the sulfur emission caps required by the 1990 Clean Air Act (Environmental Protection Agency, 1990), resulting in many consumers switching to western coal with low sulfur content (Tobin, 1984). A

wide array of other solutions have been implemented because of the Clean Air Act directives, including co-firing western coals with interior coals, using non-coal fuels in blend, and installing flue-gas desulfurization devices. See Hower et al. (1998) for a more complete investigation.

The ongoing installation of sulfur scrubbers into power plants will make coal from both regions with high sulfur content more attractive. This will probably lead to increased use of interior coals and increased competition amongst coal producers in the Appalachian Basin. The future development of the coal quality regulations will prove important to the coal industry. Enforcement will become a political matter and will ultimately be determined by the actions of successive governments.

6. Future production

Estimating future production can be done in many different ways, based on a wide array of assumptions for recoverable reserves, future restrictions and technological options. For example, Hubbert curves have been used to model future Chinese coal production (Zaipu and Mingyu, 2007). The approach used here is based on logistic curves and conclusions from the historical evolution of recoverable reserves. No other constraints or production limitations are considered, i.e. the future production is only limited by the recoverable reserves. Consequently, future production is only assumed to follow the logistic curves that best fit the historical data and available coal supply, in agreement with the fundamental assumptions, made by Hubbert (1956), for production of finite resources.

A reasonable estimate of the ultimate recoverable reserve can be created from the cumulative production and the recoverable reserves, based on historical data from mainly Milici (1997) and reserve data from EIA (Annual Coal Report, 2007). The recoverable reserves partly reflect restrictions and limitations imposed by various regulations; consequently the future outlook will be influenced by actual coal availability.

A second estimate is made from the cumulative production and the demonstrated reserve base, but this should be regarded as very optimistic as it completely ignores any limitations due to land-use restrictions and other availability issues. It should be explicitly noted that those states with large reserves, in both cases, will have the greatest influence on future coal production, especially the states of Montana, Wyoming, Illinois and West Virginia.

Current production of Montana coal is very small in comparison to its vast reserves, because the coal is situated a long way from the market and due to economic challenges, such as tax rates and high transportation costs. However, it should be noted that long transports do occur in various places, such as Powder River coals being used in Kentucky. Montana suffers from a railroad monopoly, which gives high transport costs, making it less economic than coal from Wyoming and it does not appear that transportation access will improve in the future (Hedges, 2007). The coal production tax rates have been more than twice as high in Montana, compared to Wyoming (Alt et al., 1983). If Montana's coal production increased significantly, the environmental effects will need to be carefully monitored. Some coal formations, such as the Tongue River are of the Powder River Basin, contain high sodium levels, which may contaminate water supplies (Cannon et al., 2007). Water from the Tongue River and its tributaries is extensively used for irrigation in both Wyoming and Montana. Potential environmental impact and contamination of rivers may cause problems and conflicts with agriculture, which is the largest economic sector of Montana.

Montana already exports around 40% of all electricity produced locally from coal and there are challenges with increasing the amount of new coal-fired power plants (Montana Department of Environmental Quality, 2008). To summarize, expansion of coal production in Montana is, at this time, not very likely.

The recoverable reserves are large enough to keep coal production from the Appalachian Basin virtually constant until 2050, when decline will occur. Increased production from the Interior area, chiefly Illinois, will be able to diminish, but not fully compensate, declining production of the Appalachian Basin. The western area contains huge reserves of subbituminous coal and will account for the largest part of future U.S. coal production (Figure 15).

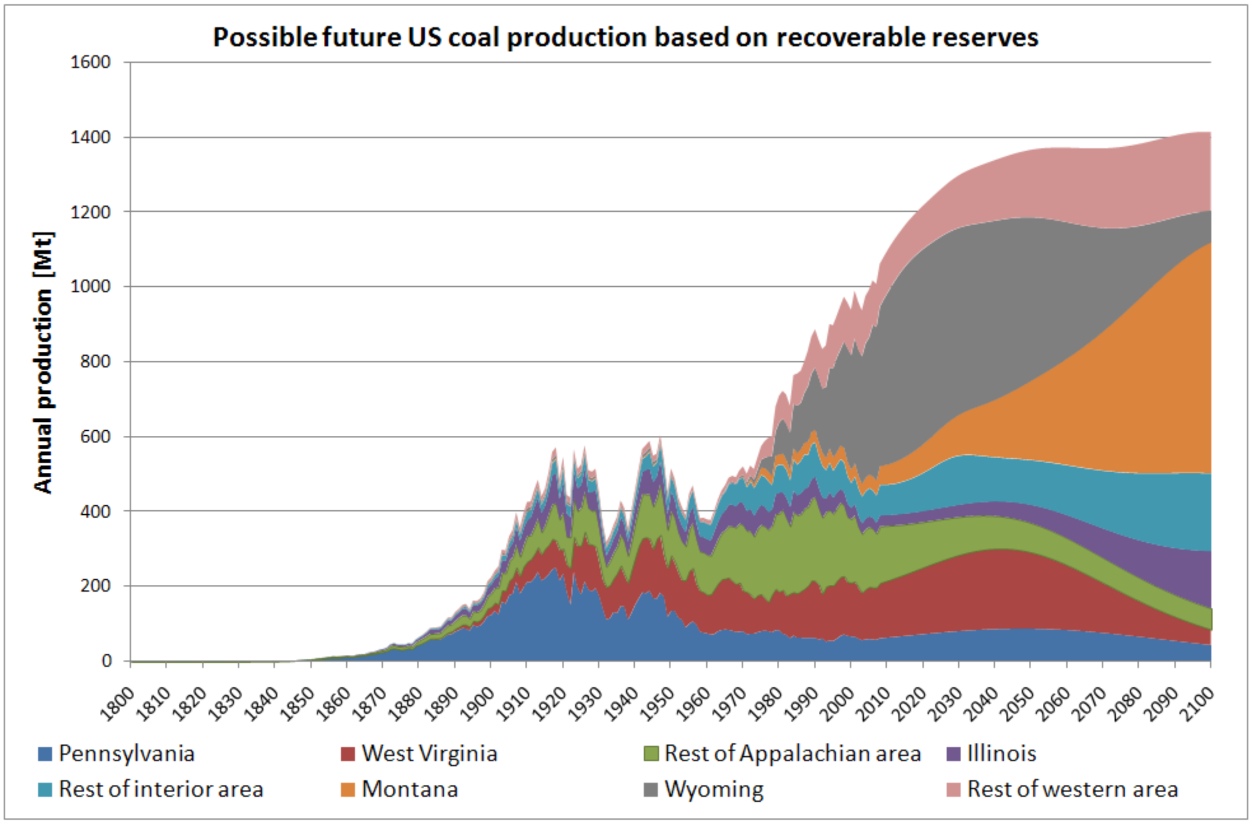

Figure 14: *Possible future U.S. coal production by area, showing the largest reserve holders. The recoverable reserves allow the production to increase to around 1400 Mt and remain there for the rest of the century. West Virginia will be the key player in keeping the Appalachian basin production constant until 2050. The rapid expansion of Wyoming production will consequently be followed by a steep decline, but this can be compensated for by the development of the vast reserves in Montana. Without the development of Montana, the US coal production could peak as early as around 2030.*

Future production will be very dependent on the future activities in Wyoming and Montana. In total, a small number of states will be key players in future U.S. supplies of domestic coal. The many states with low levels of coal production, but large coal reserves, will need to dramatically increase their production volumes to compensate the decline in other states.

If current recoverable reserves turn out to be overestimated, which cannot be excluded from the historical trend in recoverable reserves and the lack of recent assessments, future production will be even lower than forecast here. Considering the many other challenges and limiting factors (increasing mining and transportation costs from rising diesel price imposed by peak oil, future political resistance to coal power and environmental acceptability), the forecast should be regarded as optimistic. A holistic assessment of the coal utilization cycle, including geologic, socioeconomic, and political factors, will be required to better model a more accurate future outcome. In other words this analysis needs to be complemented with meticulous socioeconomic studies to cover all possible constraints to future coal production.

The demonstrated reserve base can also be used to create another possible future outcome (Figure 16). Effectively this means that all restrictions in mining are removed and all available recoverable coal can be developed, regardless of where it is located and how it is mined. If this were to occur it is possible to reach a production volume of over 2500 Mt by 2100, more than twice as much as the current output. This scenario should be regarded as an absolutely upper limit of what is possible to produce from available coal supplies under reasonable assumptions of geological availability and production trends. The aim of this forecast is to show the enormous influence of restrictions and how only geological availability can lead to very optimistic, or even unrealistic, production forecasts. This upper limit is extremely unrealistic, since coal production is an economic activity where socioeconomic and environmental issues are bound to affect production in any realistic case.

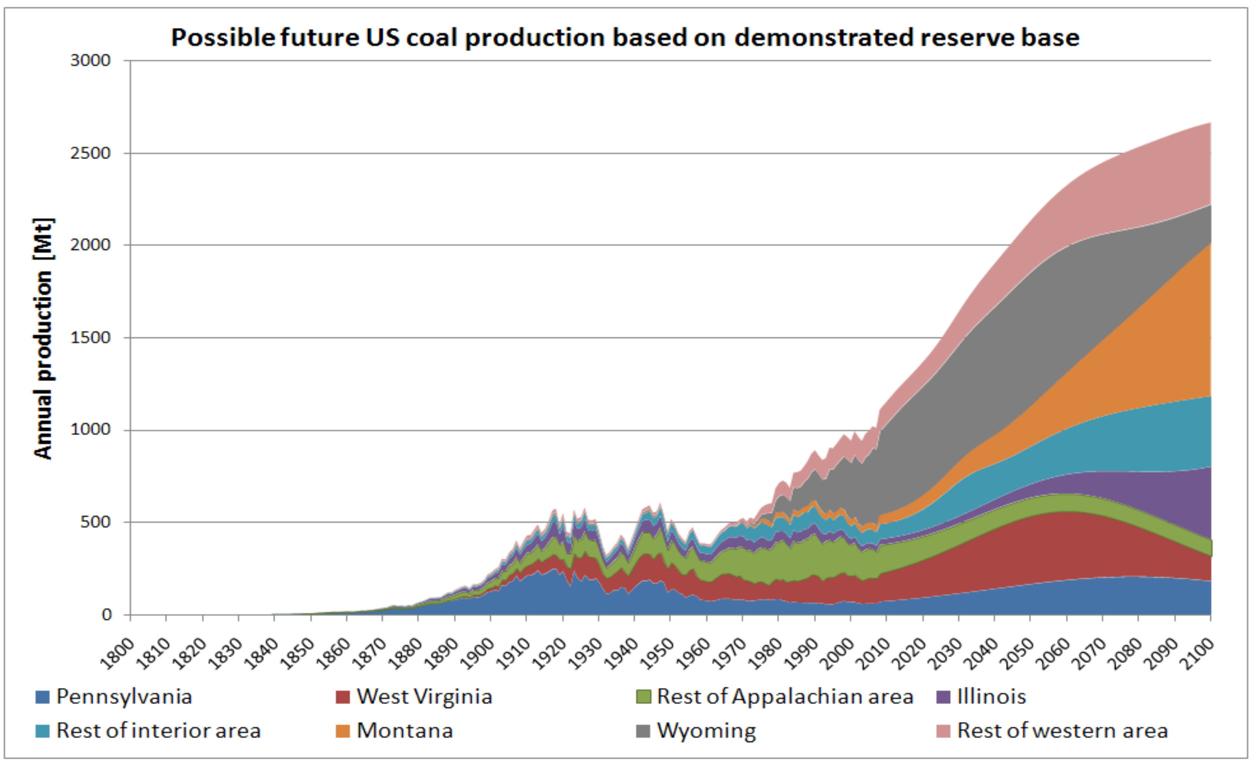

Figure 15: *Outlook based on the demonstrated reserve base. This should be regarded as an upper maximum future coal production of the United States. The production level will be able to increase over 2500 Mt annually before it will start to flatten out by the end of the century. Also here Wyoming and Montana will be the key factors, even though West Virginia also plays a significant part.*

The need to include surface and sub-surface land-use and restrictions in determining coal production figures is of great importance. These factors are essential and have enormous influence over actual production. Studies have shown that less than one-half of the total available coal resources in the examined parts of the Appalachian Basin were available for mining and only one-tenth were considered economically recoverable (Ruppert et al., 2002). This provides some perspective of the influence that restrictions, economics and coal quality issues can have on available coal amounts for future production. Also, this is a feasible explanation of the enormous differences between the forecasts (Figures 15 and 16).

7. Conclusions

The long history of coal mining in the United States has meant much prosperity, but also increased depletion as the best and most attractive seams have been extracted. Much of the "easy coal" has been produced. Generally, the coal regions in the United States are mature, with the largest and most promising formations since long discovered, assessed and developed (Milici, 1996). Future production will come from geologically more complicated formations or deeper seams. Consequently, depletion will be an important challenge and questions about whether or not it can be offset by new technology and mining methods must be asked. Almost 70% of the U.S. coal production comes from surface mines (Annual Coal Report, 2007). Accordingly, it will be challenging to mine coal at the current costs once this fraction of the coal is depleted.

Future coal production will not be entirely determined by what is geologically available, but rather by the fraction of that amount that is practically recoverable. Society demands energy, not energy from coal. This means if this energy can be obtained less costly and more practically from other energy sources, potentially nuclear power or wind, those will be favored. Increased coal prices do not necessarily lead to increased production, increased reserves, and the transformation of resources into reserves. The price development and feasibility of other energy sources must also be considered, since it is the energy that is demanded.

Increased coal prices might therefore also be a burden for the industry as investors may move towards cheaper energy sources. Increased concern around CO_2 emissions from coal is likely to decrease coal's price competitiveness, because of the potential from CO_2-taxes and increased costs of carbon-capture and storage (CCS). A closer discussion of this is beyond the scope of this study, but has been performed by others (Kavouridis and Koukouzas, 2008). There is a common belief in some form of self-regulating coal supply cycle (Thielemann et al., 2007), where increased prices and human ingenuity will automatically lead to reserve growth and higher production. Our results suggest that this theory should be reevaluated.

The historical evolution of U.S. coal reserves shows a trend towards reduced recoverable reserves. There are a number of different factors causing this, ranging from land-use restrictions to changes in definitions. The historical trend towards reduced recoverable amounts is clear and likely to continue in to the future, with even stricter regulations imposed by increased environmental concern.

A steady decline in the heating value of U.S. coal has also been observed and this can be seen as a sign of the increased depletion and the movement to less optimal seams. This trend is likely to continue in to the future, justified by increased depletion of high energy coals in Appalachia and an overall increased dependence on subbituminous western coals. By 2030 the average calorific value could be slightly above 20 MJ/kg. This also implies that the coal

production forecast in the International Energy Outlook (2007) would require the production volumes in 2030 be 70% higher than today. Whether this can be achieved is very questionable as shown by the historical production trends and the depleting reserves in many key producing states.

Using the recoverable reserves as an estimate of what is realistically available for production will yield a coal output of around 1400 Mt by 2030 through the rest of the century. This would require a massive development of the coal reserves in Montana, as they are the largest undeveloped reserves remaining for future exploitation. Unless this happens, US coal production could reach a peak around 2030.

The demonstrated reserve base allows a significantly higher production volume to be reached but this should be regarded as unrealistic, as it completely ignores regulations and restrictions. The restrictions have proved to be a key factor for the amount of coal available for production and ignoring restrictions when creating possible future scenarios is a fundamentally flawed approach.

To summarize the geologic amounts of coal are of much less importance to future production than the practically recoverable volumes. The geological coal supply might be vast, but the important question is how large the share that can be extracted under present restrictions are and how those restrictions will develop in the future. Production limitations might therefore appear much sooner than previously expected.

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